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AN OPTIMAL LOCATION OF ELLIPTICAL CROSS BORE IN ELASTIC PRESSURIZED THICK CYLINDERS

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ABSTRACT

Finite Element Analysis (FEA) was performed on elastic pressurized thick walled cylinder to determine the optimal location for an elliptical shaped cross bore. Preliminary investigations were performed on a radial elliptical shaped cross bore to establish an optimum diameter ratio in a cylinder with thickness ratio of 2.0.The cross bore diameter with size ratio of 2.0 gave the lowest Stress Concentration Factor (SCF) at 1.89.Henceforth,only the optimal diameter size ratio was used for further optimal analyses. The optimization process was then done on cross bored cylinders of thickness ratios of 1.4 up to 3.0 at various offset locations along the radial X axis of the cylinder. The study covered offset locations between the radial position of the cylinder and the offset ratio of 0.9. The authors established that offsetting of an elliptically shaped cross bores increases the magnitude of SCFs. Overall, lowest SCF occurred at radial position when K=2.5 with a magnitude of 1.733. This lowest SCF magnitude indicated a reduction of pressure carrying capacity of 42.3% in comparison to a similar plain cylinder without a cross bore.

KEYWORDS: Pressure Vessels, Optimal Location, Elliptical Cross Bore & Stress Concentration Factor

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Original Article

INTRODUCTION

High pressure vessels are some of the essential accessories in the industry. They are used for storage, industrial processing and generation of power under high pressures and temperatures [1]. The design of pressure vessels takes into consideration the vessel failure modes, induced stresses, selection of materials, the surrounding environment and stress concentration [2].

At the manufacturing stage, transverse holes or openings commonly referred to as cross bores [3] are drilled in the wall of plain pressure vessels [4]. These cross bores give provision for fitting relief and safety valves, bursting discs, gas inlets, flow circuit meter, temperature and internal pressure measurement, inspection covers, lubrication etc. [1, 5]. Therefore, the cross bore strategy is inevitable in any pressure vessels [1].

Nevertheless, these cross bores introduce geometric discontinuities that alter the uniform stress distribution along the cylinder [6]. The geometric discontinuities act as stress raisers, thus creating regions of high stress concentration especially near the intersection of the main bore and the cross bore [7]. Regrettably, at these regions of high stress the elemental stress equations cease to apply [8].

Stress Concentration Factor (SCF), also known as the Effective Stress Factor (ESF) [9], is determined using the relationship given in Equation (1) as detailed in Masu and Craggs [7] and Kharat and Kulkari [8];

$$\mathrm{SCF} = \frac{\text{Maximum hoop stress in a cross bored cylinder}}{\text{Corresponding hoop stress in a cylinder without a cross bore}} \tag{1}$$

Cole *et al*. [10] reported that high values of SCF act as points of weakness leading to reduction in the vessel strength as well as its fatigue life. This weakness reduces the pressure carrying capacity of the pressure vessel by up to 60 % [11] when compared to a plain vessel without a cross bore. It is worth noting that failures of pressure vessel are usually catastrophic and may lead to loss of life, damage of property or pose a health hazard [4, 8].

As a result, there is a need for pressure vessel designers to ensure minimum SCF arising from introduction of cross bores. For instance, in the design and manufacture of components such as shafts, valves seats, forging etc., blending geometry technology has been extensively used to reduce the SCF [7]. It is, therefore, necessary to design for an optimal minimum hoop stress concentration in order to reduce the occurrence of fatigue failures.

Stress concentrations in high pressure vessels with a cross bore depend on the geometric configuration of the cross bore [8]. The major geometric configuration parameters of the cross bore are the size ratio (cross bore to main bore ratio), location, shape, obliquity angle and thickness ratio.

Various cross bore sizes and shapes have been used in the design of pressure vessels. The cross bore size ranges from small drain nozzle to large handholds and manholes such as tee junctions [8]. While, the most common cross bore shapes are circular and elliptical [12]. A circular cross bore is termed as small when the ratio of the cross bore to main bore diameter is ≤ 0.5. Whereas, a bore ratio ranging between≥ 0.5 and≤ 1, is referred to as being large [13]. In contrast, the description of elliptical shaped cross bore is based on the diameter ratio and the orientation of major and minor diameters with the principal axes of the cylinder [10, 14].Cross bores are referred to as radial when they are drilled at the centre axis of the vessel. On the other hand, cross bores are classified as offset when drilled at any other chord away from the vessel centroidal axis [15]. Since at the offset position the axes of the cross bore and that of main cylinder bore do not intersect. Lastly, a cross bore is termed as being oblique whenever its axis is not normal to the generator of the main cylinder [16].

Studies with the aim of reducing SCF across the cross bore have been carried out. Most of these studies were centered on some configuration parameters of the cross bore. Kihiu and Masu [1] reported that chamfered cross bore reduces SCF, although it introduces other points of peak stresses along the chamfer. Moreover, the authors established that a carefully polished chamfer at the intersection of the cylinder and the hole, also reduces SCF. In more recent studies by Kihiu [17] and Quider [18], it was reported that SCF increases with decrease in the cylinder thickness ratio.

Cole *et al.* [10] and Makulswatudom *et al.* [15] reported that SCF can be reduced by making elliptical shaped cross bore positioned along the cylinder radial line instead of circular shaped holes. The two studies also reported that SCF reduces when circular shaped holes are offset by an appropriate distance from the cylinder radial line. According to Masu and Craggs [7] offsetting the position a circular cross bore from the radial line also improves the fatigue life of the cylinder by up to 170%. However, only very few studies on radial elliptical shaped cross bores have been done. Besides, the available data from these studies on the effects of offsetting an elliptical shaped cross bores on stress concentration in pressure vessels is not exhaustive. Therefore, this study seeks to determine an optimal location for an elliptical shaped cross bore in elastic pressurized thick walled cylinders.

METHODOLOGY

Seven cylinders with different thickness ratio (K) of 1.4, 1.5, 1.75, 2.0, 2.25, 2.5 and 3.0 were studied. These wall thickness ratios were selected to coincide with those discussed in the reviewed literature by Makulsawatudom *et al.*, [15]; Masu [19]; and Nihous *et al.*, [20]. Throughout this study, the radius of the main bore and the major diameter of the cross bore was kept constant at 0.025 m and 0.0025 m, respectively. These dimensions were chosen to coincide with those reported by the same authors from a previous study on optimum offset circular cross bores for purposes of comparison. The comparison of the results between these two cross bore shapes were presented elsewhere.

FINITE ELEMENT MODELLING

Three dimensional linear finite element modelling analyses were performed on the high pressure vessels with radial and offset cross bores using a commercial software program called Abaqus version 6.16. Owing to the symmetrical configuration of the pressure vessel, only an eighth of the structure was analysed. In this work, a total of 45 different part models were created and analysed.

A three dimensional deformable solid body was created by drawing an eighth profile of the pressure vessel face. The face of the pressure vessel was then extruded to form the depth of the cylinder. The depth of the cylinder was made three times the cylinder's external diameter to restrict the closed ends closures effects of the cylinder from being transmitted to the other far of the cylinder. The cross bore was formed at the creation step using cut revolve technique while applying full boundary constraints. One of the model profiles created at this stage is shown in Figure 1

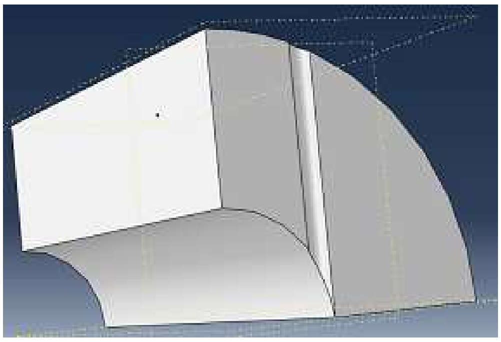

Figure 1: Part Profile For K= 2.5 Having Offset Elliptical Cross Bore at 0.685 Offset Ratio

In this FEA modelling, a linear elastic model with material properties as indicated in Table 1 was assumed throughout. The material properties chosen for this simulation were similar to those cited in references [21, 22].

Table 1: Material Properties for the Static Analysis

Parameter	Value
Young's Modulus of Elasticity	190 GPa
Poisson's ratio	0.29
Density	7800 Kg/m^3

The section properties of the model profile were defined as being solid and homogenous. This action was then followed by the creation of a single assembly. The preceding procedures allowed the creation of a part instance that is independent of the mesh. The profile of the model was then oriented in line with the global Cartesian co-ordinates axes i.e. X, Y and Z axes.

The analysis to be used for this simulation was configured by creating a static pressure step. It is worthwhile to mention that the application of different types of loads and boundary conditions are interlinked with each analysis steps. Symmetry boundary conditions were then applied at each of the three cut sections of an eighth profile of the cylinder. These symmetry boundary conditions were applied at cut regions in X, Y and Z axes thus preventing any rigidity movement.

The pressure vessel was loaded with an internal pressure at both the main bore and the cross bore. In line with the standard practice used in pressure vessel analyses the internal pressure was taken as 1 MPa [23]. In addition, a uniform axial stress σ_z, was calculated using equation 2 for each thickness ratio. The magnitudes of axial stress calculated were then applied at the far end of each corresponding vessel to simulate the end effects generated by the closed end closures in the pressure vessels.

$$\sigma_z = \frac{p_i}{K^2-1} \tag{2}$$

Where

P_i is the internal pressure.

K is the thickness ratio

The model mesh was done by dividing the model into small geometrical sections. The mesh around the cross bore region was biased by increasing the number of elements. This increase in the number of elements is referred to as mesh density. Usually, the high mesh density increases the capture of localised stress concentration [24]. For this work, the element size of the mesh chosen ranged from 0.003 m to 0.004 m.

According to the Abaqus software guideline, only second order hexahedral and tetrahedral elements are preferred for stress concentration problems. Thus, in all the studied models, only second order C3D10 tetrahedral elements with 10 nodes were used for meshing. Since tetrahedral elements are less sensitive to the initial shape of the element, therefore, their vulnerability to distortion is low [24]. A meshed profile of one of the model parts is shown in Figure 2.

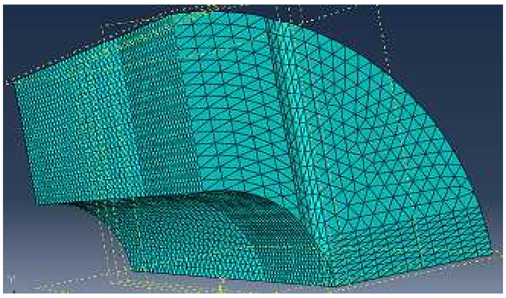

Figure 2: Mesh Profile For K= 2.5 Having Offset Elliptical Cross Bore at 0.685 Offset Ratio

VALIDATION OF THE MODEL

Primarily, the accuracy of the results depends on the quality of the mesh and its density. In this study, the verification of the results as well as the mesh convergence, were done by comparing the displacements and FEA stresses (hoop, radial and axial), with their corresponding analytical results in areas far away from the cross bore [11]. Usually the effects of any discontinuity is limited to its surrounding area. For a cross bore, the effects are limited to the surrounding

region, approximated to be linear length of 2.5 cross bore diameters [11]. In addition, other published data on related work in the reviewed literature was also used to validate the model.

DETERMINATION OF THE OPTIMAL DIAMETER RATIO FORAN ELLIPTICAL CROSS BORE

The dimension of the major diameter 'a' of the elliptically shaped cross bore was kept constant at 0.0025 m. While the minor diameter 'b' was varied between major to minor diameter ratios ($^{a}/_{b}$) of 0.2 and 4.0.This cross bore configuration is shown in Figure 3.

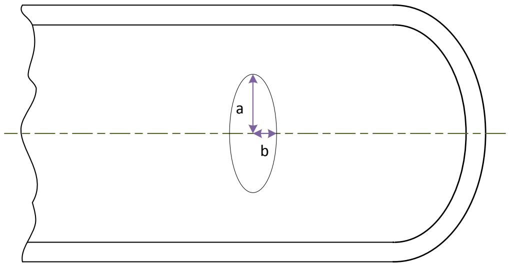

Figure 3: Elliptical Opening in a Cylindrical High Pressure Vessel

Preliminary investigations were then carried out to establish the optimal diameter ratio that gives minimum SCF. A cylinder with a thickness ratio of 2.0 was arbitrarily chosen. Ten different cross bores with major to minor diameter ratios of 0.2, 0.5, 0.915, 1.0, 1.33, 2.0, 2.25, 2.5, 3.0 and 4.0 were studied

LOCATION OF THE CROSS BORE

The optimum elliptical cross bore obtained from the preceding section was then positioned at different points along the radial X axis of the cylinder. The arrangement of the cross bore is illustrated in Figure 4.

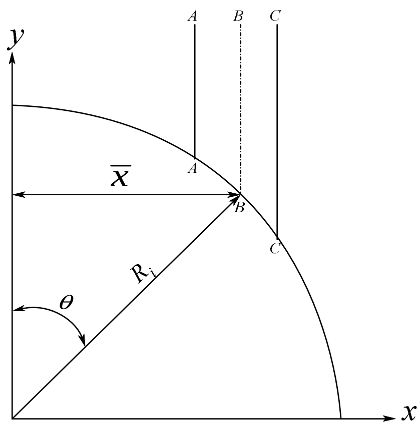

Figure 4: Configuration of an Offset Cross Bore

Where

$\bar{x}$ is the actual offset distance

R_i is the main bore radius

θ is the included angle

For the results to be compared directly with the existing literature, the actual offset position in the cylinder were converted to either offset location ratio or an included angle. The actual offset distance was divided by the main bore radius, i.e., $\bar{x}/R_i$, to give the offset location ratio. These offset ratios can also be presented in form of the included angle θ by using the trigonometric relationship between $\bar{x}$ and R_i.

Five offset location ratios were investigated. These included offset location ratios of 0, 0.24, 0.48, 0.685 and 0.9. The offset ratios chosen at 0.48 and 0.9 were relatively similar to those suggested in the technical literature by Cole *et al.* [10] and Masu [25] on circular offset cross bores. Whereas, the rest of the offset ratios were chosen arbitrarily at the mid location to investigate the stress behaviour at those points.

STRESS CONCENTRATION FACTOR

The definition of theoretical SCF indicated in equation (1) was adopted in this work. The localised critical hoop stresses in a cross bored cylinder was divided with corresponding one in a similar cylinder without a cross bore. This definition of SCF outlines the intensity of stress concentration at each point. It is important to mention that fatigue crack is likely to initiate at the surface of the component with high magnitudes of hoop stresses. Besides, in most engineering works the design is based on the highest stress magnitudes. To this end, therefore, the SCF magnitudes for each model were calculated at the points with highest stress peaks.

RESULTS AND DISCUSSION

Optimal Diameter Ratio

The magnitudes of maximum hoop stress concentration factor obtained in this preliminary investigation are illustrated in Figure 5.

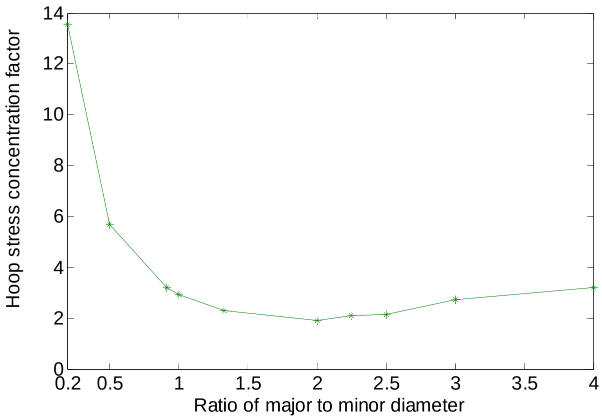

Figure 5: Hoop SCF for Radial Elliptical Cross Bore in a Cylindrical Vessel with K = 2.0

The diameter size ratio of 2.0 gave the lowest SCF at 1.89. Whereas, the highest SCF occurred at the diameter ratio of 0.2 with a magnitude of 13.533. The shape of the cross bore becomes a circular at the diameter size ratio of 1. The SCF magnitude given by this circular cross bore was higher than that of the diameter size ratio of 2 by 54.86 %. This finding was in agreement with a previous study by Harvey [14] on thin walled cylinders.

The diameter size ratio of 2 was then selected as the optimal diameter size ratio in elliptically shaped cross bores. Therefore, only this optimised diameter ratio was considered for further optimal analyses in the current study.

Location of Maximum Principal Stress in the Cylinder

The locations of maximum principal stresses on the cylinder due to the introduction of an offset elliptical cross bore is tabulated in Appendix 1 for various thickness ratios. The data is presented in the form of the main cylinder radius and the corresponding horizontal distance measured from the transverse plane of the cylinder.

With the exception of K= 2.25 and 3.0, the radial location of the maximum stress peaks in the cylinder occurred away from the cross bore intersection, signifying stress transition points. Probably from the plane stress to plane strain. In fact, the position of the maximum principal stress in the cylinder occurred close to plane CC (see Figure 4). This trend implied that any increase in offset location ratio results to an increase of the hoop stress.

Moreover, the location of the maximum principal stress in the cylinder, defined in terms of radial and transverse positions, also signified the presence of a high stress concentration factor in the cylinder. Usually, in pressure vessels design, the use of reinforcement pads are recommended whenever the maximum hoop stress is anticipated to occur close to the outside surface of the cylinder in order to prevent any failure

Effects of Elliptical Cross Bore Location and Thickness Ratio on Hoop Stress Concentration Factor

The graphs showing the variation of hoop stress concentration factors with offset locations and thickness ratios are shown in Figures 6 and 7, respectively.

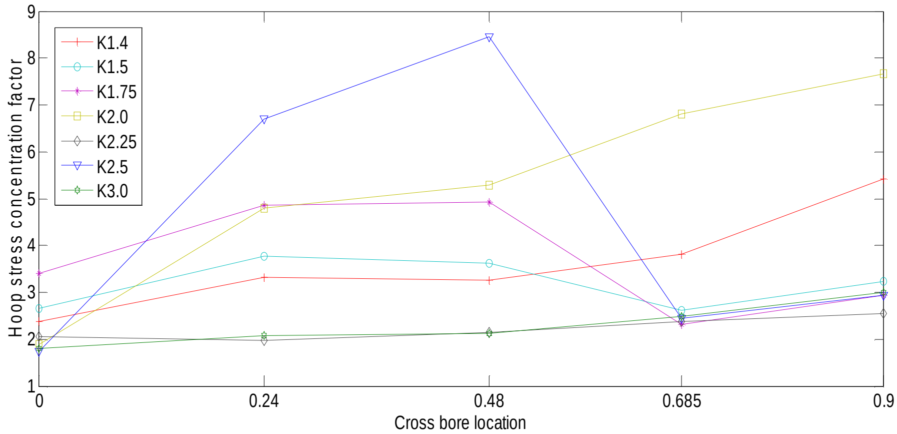

Figure 6: Hoop SCF vs Cross Bore Location due to an Elliptical Cross Bore

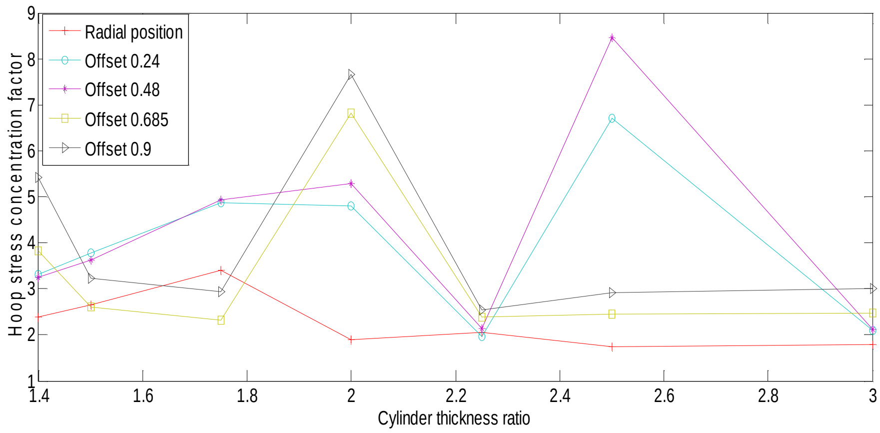

Figure 7: Hoop SCF Vs Cylinder Thickness Ratio Due to an Elliptical Cross Bore

With the exception of K=1.5 and 1.75, the lowest magnitudes of hoop stress concentration factor in a thick cylinder with elliptical cross bore occurred at the radial position, ranging from 1.733 to 2.375. As illustrated in Figures 6 and 7, it was generally observed that the stress concentration factors due to the elliptical cross bore tend to increase with increasing offset location ratio. The highest SCF peaks were observed at the 0.48 and 0.9 offset positions for K=2.5 and 2.0, with respective magnitudes of 8.457 and 7.661. These high peaks were attributed to the location of maximum hoop stress being close to the outside surface of the cylinder. Conversely, the thickness ratio of 2.25 gave the lowest SCF magnitudes for all offset positions except at 0.48. At 0.48 offset position, the minimum SCF occurred at K=1.75. As tabulated in Appendix 1, the location of these lowest SCFs in the cylinder were found to occur at the intersection between the cross bore and the main bore. Remarkably, the overall best results occurred in K=2.25 as illustrated in Figure 7. Nevertheless, the overall lowest SCF occurred at K=2.5 with a magnitude of 1.733. This lowest SCF magnitude indicated a reduction of pressure carrying capacity by 42.3% in comparison to a similar plain cylinder without a cross bore. An improvement from the 60% reduction cited earlier by Masu [11].

DISCUSSION OF THE RESULTS

Several studies (Harvey [14], Makulsawatudom *et al.* [15], Nihous *et al*. [20], Timoshenko [26], Faupel and Harris [27], Adenya [28]) on elliptically shaped holes, have been carried out previously. In these reviewed studies, the optimal cross bore diameter size ratio was 2. In addition, the minor diameter of the cross bore was placed parallel to the axial direction for cylinders. These two configurations had earlier been proven in preceding section to give minimum SCF magnitudes. A comparison between results from the present study and those reported in the reviewed literature is summarised in Table 2.

Using the expression cited by Nihous *et al.* [20] and Timoshenko [26], the minimum SCFs that can be obtained from an optimally sized elliptically shaped hole in a plate under uniaxial or biaxial loading is 2.0 and 2.5, respectively. Whereas, the corresponding maximum SCFs values are 5.0 and 4.5. Further, another study by Harvey [14] gave a minimum SCF of 1.5 for a thin cylinder having an optimum sized and correctly configured elliptical cross bore.

Table 2: Comparison of SCF for Radial Elliptical Optimum Cross Hole in Cylinders and Plates

Author	Description	SCF
Nihous *et al.* [20] & Timoshenko [26]	Plate with elliptical hole at the centre under uniaxial loading	2.0 (min) 4.5 (max)
	Plate with elliptical hole at the centre under biaxial loading	2.5 (min) 5.0 (max)
Harvey [14]	Thin cylinder with radial elliptical cross bore	1.5
Faupel and Harris's [27]	Thick cylinder with radial cross bore regardless of its size	1.5
Adenya [28]	Cylinder with K = 2.0, 2.25 & 2.5 with radial elliptical cross bore	< 2.0
Makulsawatudom *et al* [15]	Cylinder with K = 2.0 with radial elliptical cross bore	2.01
Present study	Cylinder with K = 2.0 with radial elliptical cross bore	1.898
	Cylinder with K = 2.25 with radial elliptical cross bore	2.05
	Cylinder with K = 2.5 with radial elliptical cross bore	1.733

Faupel and Harris's [27] study gave a SCF of 1.5 for a radial elliptical cross bore in a closed thick walled cylinder, regardless of the cross bore size. While in a similar elliptical cross bore, Adenya [28] gave a maximum SCF of 2.0 after investigating three cylinders with thickness ratios 2.0, 2.25 and 2.5. These results by Adenya [28] study compared favourably with those presented in this study. For instance, in this study, the SCFs for radial elliptical cross bores for K=2.0, 2.25 and 2.5 were found to be 1.898, 2.05 and 1.733, respectively. Another study by Makulsawatudom *et al.* [15] gave the SCF by a radial elliptical cross bore for K=2.0 as 2.01 comparing well with 1.898 obtained in this study. In general, optimum configured elliptical holes in the plates were noted to give fairly similar SCF magnitudes to those of radial elliptical cross bores in a thick cylinder.

The study by Makulsawatudom *et al.* [15] had investigated the effects of offsetting of elliptical cross bores in a single offset position. However, the offset results presented by this authors were ignored due a description error noted during the selection of the optimal offset position.

Generally, it was observed that the SCF increased as the cross bore location moved further away from the radial axis of the main cylinder. This occurrence was attributed to the cross bore shape which resembled an ellipse when viewed at the intersection between the cross bore and the main bore. In an ellipse, the major diameter denoted as 'a', is parallel to the axial direction of the cylinder. Whereas, the minor diameter denoted as 'b', is parallel to the direction of the hoop stress. The minor diameter increases with increase in the offset position ratio. This cross bore configuration where $a < b$ results in high magnitudes of hoop stress in the cylinder as cited by Harvey [14]. The configuration is contrary to that observed in offsetting of the circular cross bore by Cheng [5] study.

Graphs showing optimal SCF magnitudes at each thickness ratio and offset position for an offset elliptical cross bore are exemplified in Figures 8 and 9.

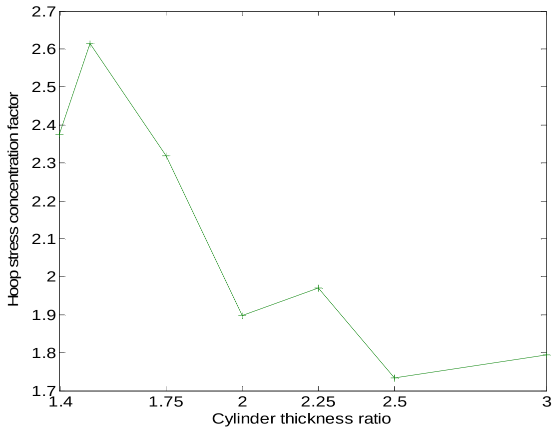

Figure 8: Optimal Hoop SCF Vs Thickness Ratio

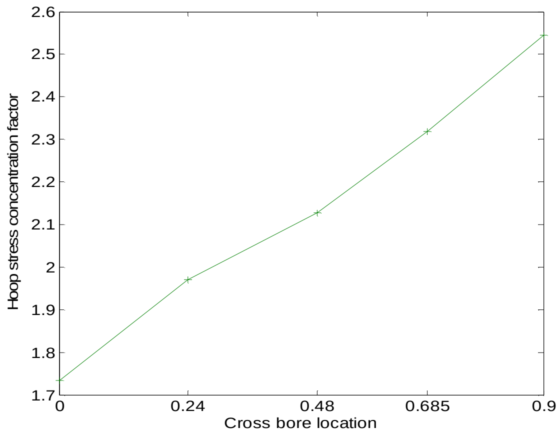

Figure 9: Optimal Hoop SCF Vs Cross Bore Location

As illustrated in Figure 8, the lowest and highest hoop stress concentration occurred in K =2.5 and 1.5, respectively. This observation confirmed that the structural integrity of the vessel is fairly affected by its thickness ratio. Further, it was shown in Figure 9 that, offsetting an optimum elliptical shaped cross bore significantly increases the hoop stress concentration.

CONCLUSIONS

The cross bore diameter with size ratio of 2.0 gave the lowest stress concentration factor (scf) at 1.89, when the cross bore was position radially for k= 2.0. In addition, the study established that offsetting of elliptically shaped cross bores increased the magnitude of scfs. overall, lowest scf occurred at radial position when k=2.5 with a magnitude of 1.733. This lowest scf magnitude indicated a reduction of pressure carrying capacity of 42.3% in comparison to a similar plain cylinder without cross bores.

LIST OF ABBREVIATIONS

K Thickness ratio (outer diameter to inner diameter)

SCF Stress Concentration Factor

a Major diameter

b Minor diameter

ACKNOWLEDGEMENTS

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APPENDIX 1

Table 3: Location of the Maximum Hoop Stress in the Cylinder Due to an Offset Elliptical Cross Bore

K	Offset Ratio	Actual Offset Distance $\bar{x}$m	Distance of the Cross Bore Configuration Measured from the Transverse Axis of the Main Cylinder			Position of Maximum Principle Stress in the Cylinder	
			Plane AA	Plane BB	Plane CC	Radius R (m)	Horizontal Distance $\bar{x}$, Measured from the Transverse Axis of the Main Cylinder
1.4	0	0		0	0.0025	0.0336	0.0025
	0.24	0.006	0.0035	0.006	0.0085	0.035	0.0085
	0.48	0.012	0.0095	0.012	0.0145	0.035	0.0145
	0.685	0.017125	0.014625	0.017125	0.019625	0.035	0.019625
	0.9	0.0225	0.02	0.0225	0.025	0.035	0.025
1.5	0	0		0	0.0025	0.0359	0.0025
	0.24	0.006	0.0035	0.006	0.0085	0.0375	0.0085
	0.48	0.012	0.0095	0.012	0.0145	0.0375	0.0145
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.019625
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.025
1.75	0	0		0	0.0025	0.0422	0.0025
	0.24	0.006	0.0035	0.006	0.0085	0.04375	0.0085
	0.48	0.012	0.0095	0.012	0.0145	0.04375	0.0145
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.014625
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.020158
2.0	0	0		0	0.0025	0.0265	0.0024567
	0.24	0.006	0.0035	0.006	0.0085	0.0475	0.008392
	0.48	0.012	0.0095	0.012	0.0145	0.05	0.01439
	0.685	0.017125	0.014625	0.017125	0.019625	0.05	0.019625
	0.9	0.0225	0.02	0.0225	0.025	0.05	0.025
2.25	0	0		0	0.0025	0.025	0.000491
	0.24	0.006	0.0035	0.006	0.0085	0.025	0.007933
	0.48	0.012	0.0095	0.012	0.0145	0.025	0.00969
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.014625
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.02
2.5	0	0		0	0.0025	0.025	0.000491
	0.24	0.006	0.0035	0.006	0.0085	0.052	0.0085
	0.48	0.012	0.0095	0.012	0.0145	0.0625	0.0145
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.014625
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.02
3.0	0	0		0	0.0025	0.025	0.0017648
	0.24	0.006	0.0035	0.006	0.0085	0.025	0.00793
	0.48	0.012	0.0095	0.012	0.0145	0.025	0.00969
	0.685	0.017125	0.014625	0.017125	0.019625	0.025	0.01463
	0.9	0.0225	0.02	0.0225	0.025	0.025	0.02